Center for Aerospace Structures
Department of Aerospace Engineering Sciences
University of Colorado at Boulder

A Theoretical Basis for Microdynamic Design and Analysis

Structural Mechanics Branch
NASA Langley Research Center

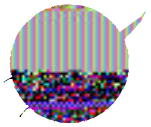
Prof. Lee D. Peterson
Lisa R. Hardaway

Center for Aerospace Structures
Department of Aerospace Engineering Sciences
University of Colorado at Boulder

Dr. Mark S. Lake
NASA Langley Research Center

Presented at the June 1999 Microdynamics Workshop
Pasadena, California

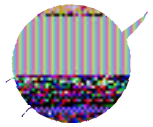
Research Sponsored by
NASA LaRC, NASA JPL and Foster-Miller, Inc.



Presentation Objectives

- Propose a Specification of Microdynamic Exceedance Modes for Precision Structures
  - *Loads*
  - *Manifestations*
  - *Design, Analysis and Verification*
- Theoretical Exceedance Analysis Examples
  - *IPEX Boom ("Mode 1 Exceedance Assessment")*
  - *SIM Hexapod ("Mode 3 Exceedance Assessment")*

Microdynamic Exceedance Modes provide a logical framework for discriminating phenomena and developing design requirements and specifications



Structural Design Practice Provides an Important Precedent for Defining Microdynamic Design Principles

- Example: Structural Fatigue and Failure Analysis
  - Identifies and specifies failure modes

    Mode 1 Fatigue Failure
  - Identifies and specifies analysis requirements to assess these failure modes in a design

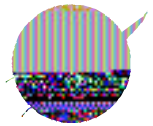
    K1 Stress Concentration Factor

- Analyses are part of standard finite element codes (e.g. Abacus)

  Lead directly to design analysis and verification specifications

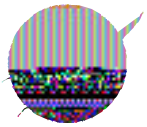
How Do We Define Microdynamic Exceedance Modes?

This is the First Step to Developing Microdynamic Requirements and Specifications



Microdynamics are "Interesting" if and only if …

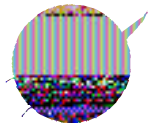
- The response of the structure
  - Disagrees with what an "known model" would predict AND is relevant to the system requirements
  - Is outside that which can be "accommodated" by a controller
- What is NOT interesting
  - Poorly measured "linear" environmental effects
  - A response which can be "precisely predicted" by a linear, identified model
  - A response that can be rejected by a controller
- But do not assume
  - Only "nonlinear" microdynamics are significant; controllers may have problems with linear microdynamics too
  - Anything not predicted or not expected is "new physics"



Definition of a "Microdynamic Exceedance Mode"

A Microdynamic Exceedance Mode is a load condition that results in a mission relevant, anomalous response at or below a microstrain of motion.

Microdynamic Exceedance Modes are distinguished by their load levels, their manifestations, and their design solutions.



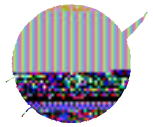
Proposed "Microdynamic Exceedance Modes"

Mode 1 Microdynamic Exceedance: Gross Sliding

Mode 2 Microdynamic Exceedance: Macroscopic Stick-Slip

Mode 3 Microdynamic Exceedance: Non-Conforming Interface Microslip

Mode 4 Microdynamic Exceedance: Roughness-Induced Microslip



Mode 1 Microdynamic Exceedance: Gross Sliding

- Loads

  Average absolute shear stress across mechanism interfaces exceeds averaged Coulombic normal stress

- Manifestations

  Permanent structural shape changes

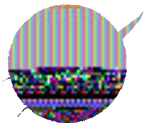
  Momentary high velocity impulse

  Harmonic distortion effects; chaotic dynamics

- Design, Analysis and Verification

  Analyze structural loads and stresses and compare to Coulombic limit

  Design structure and/or spacecraft loading conditions to not exceed the Coulombic limit



Mode 2 Microdynamic Exceedance: Macroscopic Stick-Slip

- Loads

  Average absolute shear stress in mechanism interfaces is near the Coulombic limit and the strain rate exceeds the Stribeck limit

- Manifestations

  Classical stick-slip behavior (a.k.a "Static vs Dynamic Friction")

  Mode 1 effects PLUS persistent response to quasi-static loading

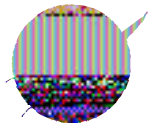
- Design, Analysis and Verification

  Analyze structural loads and compare to Coulombic limit

  Analyze dynamic strain rates and compare to Stribeck limit

  Design structure and loading conditions to not exceed the Coulombic limit or the Stribeck limit

  Possible design modifications of mechanisms to avoid effects leading to instability of friction coefficient



Mode 3 Microdynamic Exceedance: Non-Conforming Interface Microslip

- Loads

  Static or dynamic loads in non-conforming joint interfaces that are below Mode 1 and Mode 2 levels; No known lower limit

- Manifestations

  Deployment imprecision

  Microlurch and Equilibrium Zone (Warren Ph.D.)

  Hysteresis and damping

  Possible harmonic distortion in vibration response

- Design, Analysis and Verification

  Analyze coupled structure-mechanism model for harmonic distortions

  Analyze for deployment precision

  Design structure and mechanisms using "Load Path Management" (Hachkowski Ph.D.)

Mode 4 Microdynamic Exceedance: Roughness-Induced Microslip

- Loads

  Static or dynamic loads in conforming joint interfaces that are below Mode 1 and Mode 2 levels; No known lower limit

- Manifestations

  Deployment imprecision

  Microlurch and Equilibrium Zone (Warren Ph.D.)

  Hysteresis and damping

  Viscoelastic response

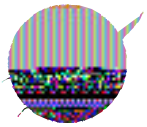
  Transient shear load-displacement response

  Possible harmonic distortion and instabilities in vibration response

- Design, Analysis and Verification

  Mode 3 approaches

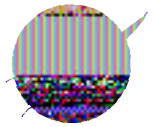
  Only moderate confidence in existing models (Hinkle Ph.D.)



"Mode N" Microdynamic Exceedance: Unknown Effects (Research Topics)

- Research should continue to look for other exceedance modes
- Possible sources:
  - Materials (composites and metal alloys)
  - Cables (probably analyze using Mode 1 through Mode 4 protocols)
  - Actuators and sensors
  - Bonded joints
- But Note:

We have no conclusive evidence that these exceedance modes or others exist, and in some cases we have (incomplete) data to the contrary …



How do we address "Un-modeled Linear Microdynamic Exceedance Modes?"

- Recall

  Do not confuse an unexpected response with "new physics."

- Challenge:

  Microdynamic experiments are at very small strain levels

  Damping approaches material limits

  Results in very high sensitivity of the structural response to thermal, mechanical and environmental loads

- An un-modeled entirely linear effect can appear to be a microdynamic exceedance mode

  A propagating disturbance can cause a high response simply from linear dynamic response

  (E.g., "thermally induced" vibrations in solar arrays)

Microdynamicists should always consider the possibility of a purely linear mechanism explaining the data

Microdynamic Regimes Based on Stress Magnitudes and Rates

- Scaling partially driven by interface surface roughness
- Generally …

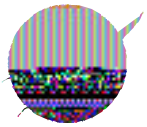
Mode 1 - above 10 microstrain in the joints

Mode 2 - above 10 microstrain per second in the joints (ill-defined in the literature)

Mode 3 - Nanostrain to microstrain

Mode 4 - Nanostrain to microstrain

Modes 3 and 4 Exceedances are the Subject of Theoretical and Experimental Research Because Little Data is Available at these Small Strains



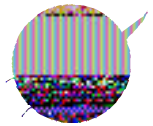
Implications for Future Missions

- We can use this framework to discriminate potential problems at the system design level and at the component design level
- Example: Scaling and the Effect of Structural Dimension on Microdynamics
- Large structures --> Large inertias --> Larger maneuver loads

  Leads to increased induction loads for all 4 exceedance modes
- Large structures --> Lower stiffness

  Leads to more compliance in the manifestation (responses) to the exceedance modes

Good microdynamic design practice will lead naturally to a high stiffness to mass ratio.



Examples of Theoretical Microdynamic Exceedance Mode Analyses

- Consider two Example Analyses

  IPEX Boom ("Mode 1 Exceedance Assessment")

  SIM Hexapod ("Mode 3 Exceedance Assessment"

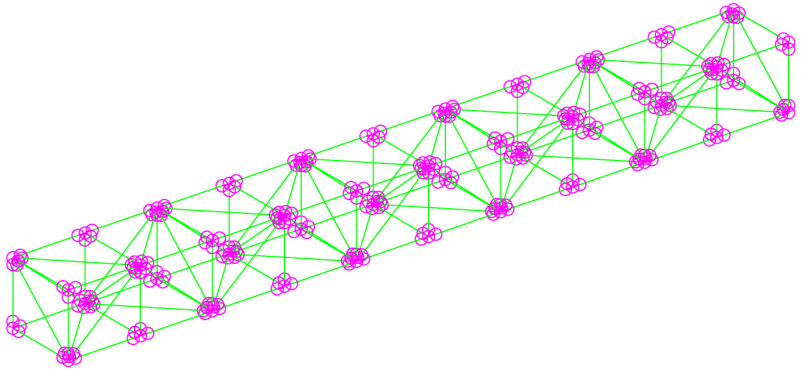
- Model using linear structural finite element model coupled to nonlinear mechanism model

  Where needed, use physical mechanism models, not empirical (I.e., "Dahl" models)

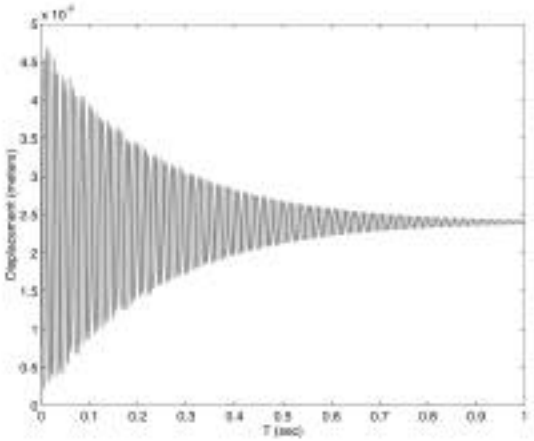
IPEX Boom "Mode 1" Exceedance Analysis

- Simulate slippage in selected joint using an enforced "gross slippage" in a selected joint
- Compare response with acceptable Mode 1 exceedance criteria (TBD)

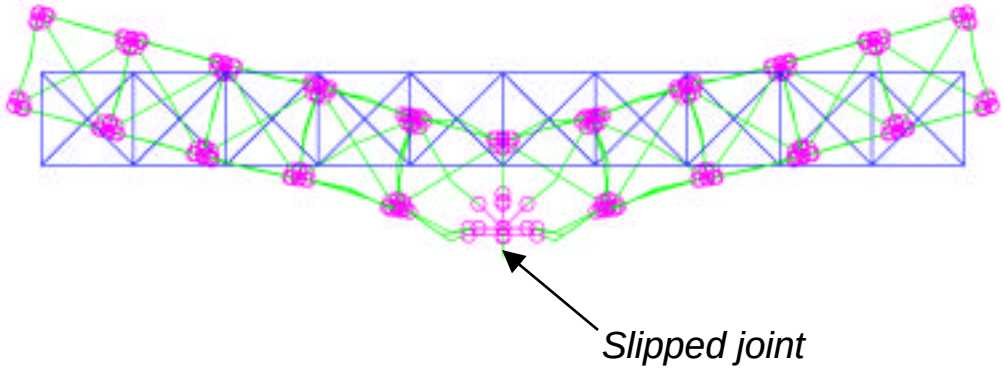
FE Model



Simulated Response



Mode 1 Exceedance



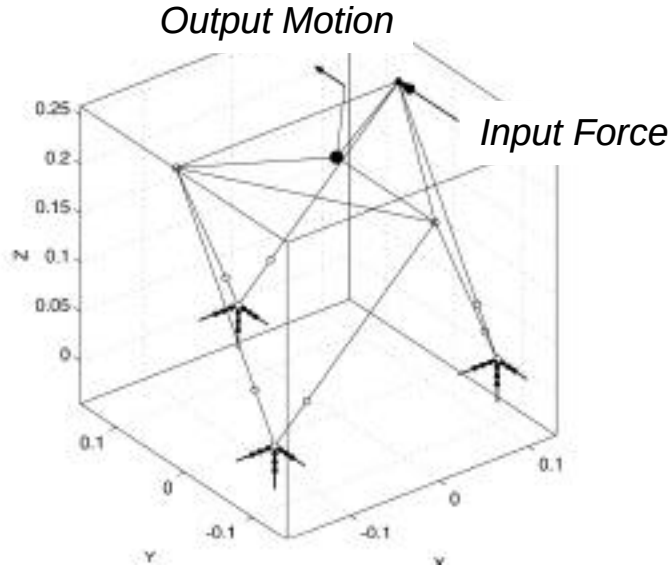
SIM Hexapod Mode 3 Exceedance Analysis

- Use coupled structure-mechanism model to assess dynamic response

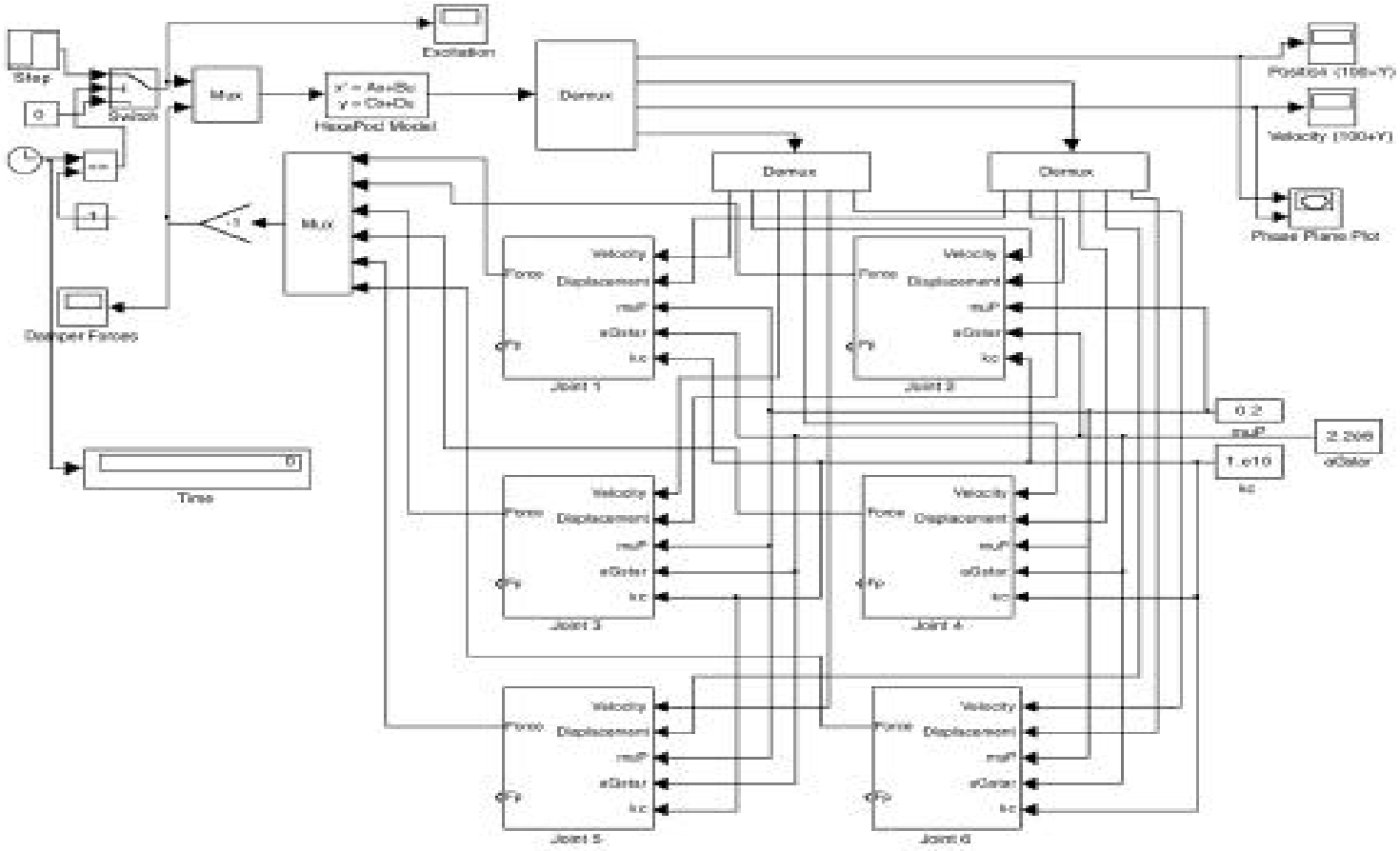
  Look for Microlurch and Harmonic Distortion effects

- Model implemented in MATLAB and SIMULINK

FE Model



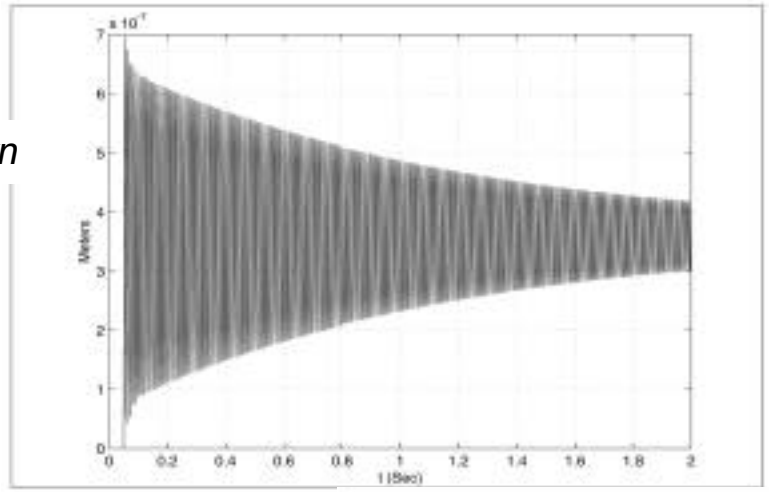
SIM Hexapod Mode 3 Exceedance Analysis



Simulation Shows Improved Response with No Apparent Higher Harmonics Related to the Mode 3 Exceedance

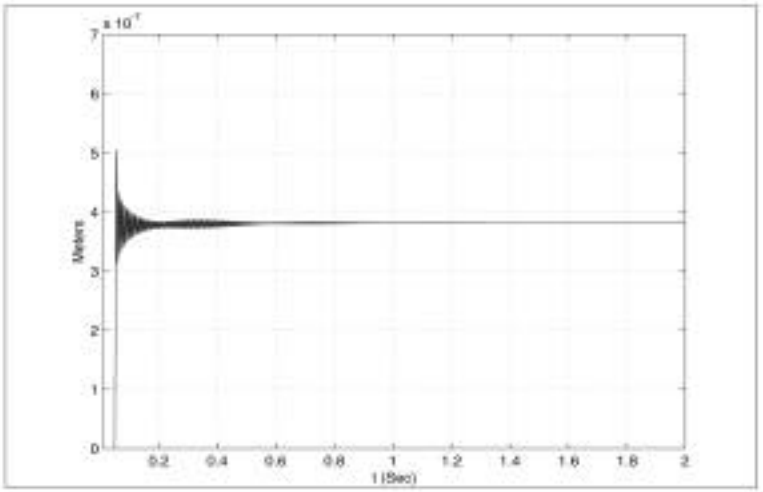
Linear Response

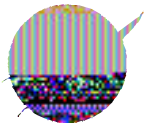
Mechanisms Locked Down



Nonlinear Microdynamic Response

Mechanisms Providing Damping





Where from Here

- Codify what we know into design guidelines and specifications
  - How to Design
  - How to Specify
  - How to Verify
- Apply theoretical modeling as best we can

  Focus on Exceedance Mode Analysis principles

  Focus on Exceedance Mode Verification principles
- Keep looking for what we don't know but suspect
  - Mission-relevant anomalies
  - Controller-confounding anomalies
  - Ground-orbit disagreement

Microdynamics Can be Designed, but Not Ignored.